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Fully reversible reinforcement of softwood beams with unbonded composite plates

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ABSTRACT

In this paper, results of flexure tests aimed at improving the structural behavior of softwood beams reinforced with unglued composite plates and at developing an effective alternative to the use of organic resins are presented. The addition of modest ratios of GFRP (*Glass Fiber Reinforced Polymer*) composite strengthening can prevent tension failure in timber beams. However the application of organic matrices presents problems of reversibility, compatibility and durability with timber and poor performance at high temperatures. The increment in capacity and stiffness and the analysis of the failure modes is the central focus of this paper. The experimental campaign is dealing with a significant number of un-reinforced and reinforced beams strengthened with unbonded GFRP plates. A 3-dimensional finite element model is also presented for simulating the non-linear behavior of GFRP-reinforced softwood beams. The ability of the numerical model to reproduce experimental results for the load–deflection curves is validated.

1. Introduction

Softwood is from gymnosperm plants and it is the basis of approx. 85% of the world's production of wood elements. Softwood as a traditional building material has been extensively used from antiquity to the present and, among softwoods, fir wood is characterized by low weight density and good performance in terms of tensile strength, is likely to distort during seasoning. Knots or grain deviation are the main causes of tension failures. Timber construction constitutes a significant part of the infrastructure in many countries: its extensive use is essentially due to its excellent workability, good mechanical properties and low weight density. Splits caused during seasoning and natural defects may highly affect its mechanical properties and particularly cause high decreases of capacity. This reduction of the tensile strength may be as high as 90% [1].

Softwood beams are usually replaced or reinforced with traditional methods involving the use of standard building materials such as steel or aluminum plates, or composite materials. Timber reinforcement is often necessary for civil infrastructures: approx. 47% of US timber bridges is structurally deficient according to the National Bridge Inventory [2].

The application of composites for strengthening of softwood beams is not new. FRPs (*Fiber Reinforced Polymers*) have high tensile strength and stiffness. The structural use of Glass and Carbon FRP composites (GFRP and CFRP, respectively) is becoming common not only for new timber members, but also for reinforcement of structural elements belonging to the architectural heritage. Composites are usually used where at least two of their beneficial properties, e.g. high tensile strength and ease of application, may be exploited. In these situations, the total cost of using composite materials is similar to metallic alternatives such as steel and aluminum plates or replacement.

There are three "traditional" methods for reinforcing timber beams with FRPs: (1) Bonding of consolidated (pultruded) laminates [3–5]; (2) Resin infusion of fabric reinforcement into grooves cut in the wood [6–11]; and (3) Wet lay up of FRP sheet reinforcement using epoxy adhesives [12–15]. According to the above procedures in the last two decades, FRP composites have been diffusively used in bridge decks, trusses, timber floors, etc. [16–19].

However the wide choice of composite products and their scattered mechanical properties can lead to serious problems for the designer. The selection of the reinforcement layout and the most appropriate material should be based on an accurate examination of the timber beams to be strengthened in order to avoid

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ineffective interventions [20,21]. The long-term durability of some FRPs also needs to be demonstrated [22,23].

Important issues remain to be solved. For example the use of FRP composites to reinforce timber beams without organic oil-based adhesives (e.g. epoxy resins) is less established. Recently, the use of natural fibers with non-organic matrixes or mechanical metal connectors has been investigated [24], and it aims at developing an interesting competitor to the use of organic oil-based fibers (e.g. CFRP) or resins, which present problems of limited durability, low reversibility and poor performance at high temperatures [25]. Governmental and local conservation bodies do not often authorize an extensive use of organic adhesives on listed timber structures and this highly limits the use of composite materials on historic constructions. Ethical guidelines for conservation works on historic constructions often list the minimal intervention and the use of appropriate materials and fully-reversible methods [26].

In the field of green building, there are several positive aspects in this research. For example, any disposal process requires sorting materials based on composition and nature and, because timber is doubtless the ultimate green building material, its preservation and use is also desirable [27].

The reinforcement method proposed in this research meets the above requirements. The results of flexure tests on firwood beams reinforced using GFRP plates, applied on the tension side without the use of an organic adhesive, are presented in this paper. Plates have been fixed to the beam's tension surface using metal screws or bolts [28,29]. Reinforcement can be easily removed, if needed, because no organic adhesives have been used for the application of the GFRP plates.

2. Material characterization

2.1. Timber

A total of 41 sharp-edged softwood beams were tested of which 28 beams were reinforced with varying amounts of tensile reinforcement. The type of softwood used in the investigation is fir wood (*Abies Alba*). The wood stock was firstly assessed by visual and mechanical grading. Bending tests were conducted on beams with two different dimensions: 95 × 95 × 2000 mm (26 beams) and 200 × 200 × 4000 mm (15 beams) (Fig. 1). Small beams are composed of solid softwood while large beams are made of laminated timber, also called, glulam. For small beams the moisture content and weight density were 14.31% (SD = 0.89%) and 417 kg/m^3 (standard deviation SD = 24 kg/m^3), respectively. European standard EN 13183-1 [30] was used to measure the moisture content. For large beams moisture content and weight density were 11.31% (SD = 0.37%) and 430.8 kg/m^3 (SD = 18 kg/m^3), respectively.

Table 1
Properties of the timber.

	Small beams	Large beams
Wood species	*Abies Alba*	
Wood type	Solid	Glulam
Weight density (kg/m^3)	417 (24.2)	430.8 (18.2)
Moisture content (%)	14.31 (0.89)	11.31 (0.37)
Specimen dimensions (mm)	20 × 20 × 60	20 × 20 × 60
Number of tested specimens	10	10
Compressive strength (MPa)	36.90 (2.06)	37.94 (2.56)
Young's modulus (GPa)	10.55 (1.81)	11.9 (1.55)

SD in ().

The mechanical properties of timber in terms of Young's modulus and compressive strength are presented in Table 1. The compressive strength varied in the range of 34.54–40.43 MPa, and the Young's modulus from 9.54 to 11.91 GPa.

2.2. GFRP plate

The GFRP plates consisted in high-volume fraction high-strength unidirectional glass fiber in a polyester resin. Plates are produced by *Fibrenet SpA* under the commercial name of *Fbprofile*. The producer data sheet reports a Young's modulus and compressive strength of 32.6 GPa and 395 MPa, respectively. Results of mechanical characterization basically confirmed these values: according to ASTM D 3039 [31] standard Young's modulus was 31.57 GPa (SD = 2.458 GPa) with a tensile strength of 368.8 MPa (SD = 30.1 MPa). The manufacture of the GFRP plate is by pultrusion process (Table 2).

For small softwood beams, GFRP plates were reduced to a length of 1400 mm and were symmetrically applied on the beam's tension side using different types of steel screws. These beams were reinforced with a single GFRP pre-drilled plate (Fig. 2).

For reinforcement of large beams, two overlapping pre-drilled rectangular plates of dimensions 3600 × 80 × 9.5 mm (length × width × height) were used. GFRP plates were epoxy glued together and connected to the timber surface using metal screws or bolts. The mechanical properties of these plates are the same of the ones used for reinforcement of small beams.

3. External strengthening

Strengthening was performed with the application of the GFRP plates before the bending loads were applied. The timber surface was cleaned by air jet to rid it of loose particles and dust. The adhering face of the GFRP plate was also cleaned by acetone. Pre-drilled GFRP plates were fixed to the timber surface using commercially available metal screws (Fig. 3a) applied according to different configurations.

For the geometrical arrangement of the screws on small beams, four configurations have been used. According to the first


a) b)

Fig. 1. (a) Small softwood solid beams. (b) Large softwood glulam beams.